

## Pseudovector mesons, hybrids and glueballs

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We consider glueball– (hybrid) meson mixing for the low-lying four pseudovector states. The  $h'_1(1380)$  decays dominantly to  $K^*K$  with some presence in  $\rho\pi$  and  $\omega\eta$ . The newly observed  $h_1(1600)$  has a  $D$ - to  $S$ -wave width ratio to  $\omega\eta$  which makes its interpretation as a conventional meson unlikely. We predict the decay pattern of the isopartner conventional or hybrid meson  $b_1(1650)$ . A notably narrow  $s\bar{s}$  partner  $h'_1(1810)$  is predicted.

The pseudovector ( $J^{PC} = 1^{+-}$ )  $s\bar{s}$  ground state has the interesting property that its OZI allowed decay to open strangeness, i.e.  $K^*K$ , which is *a priori* expected to be dominant, is severely suppressed by phase space. This not only makes the state anomalously narrow [1], but opens up the possibility that other decays could be significant. These can arise from  $u\bar{u}$ ,  $d\bar{d}$  components in the state, which can come from mixing with a glueball.

We solve Schwinger-type mass equations with linear masses, pioneered in refs. [2,3] and motivated in refs. [3–5]. In this approach the underlying nature of the meson, whether conventional or hybrid, is not specified. The primitive (bare) states are ideally mixed. Primitive isoscalar and isovector  $u\bar{u}$ ,  $d\bar{d}$  states are degenerate. In this work we further only allow  $SU(3)$  symmetric glueball–meson coupling, with no meson–meson coupling. We restrict to ground state and first excited state mesons. It is known that such restriction is quite accurate if the glueball mass is far from those of the states [5], as is the case here.

The numerical input is as follows. The ratio between pseudovector and scalar glueball masses is evaluated in lattice QCD as  $1.70 \pm 0.05$  [6] or  $1.73 \pm 0.09$  [7]. Taking the world average scalar glueball mass as 1.6 GeV [4], this implies a (input) pseudovector glueball mass of 2.7 GeV. Our conclusions do not critically depend on this value. The primitive  $u\bar{u} + d\bar{d}$  ground state is input as the  $b_1$  mass [1]. The physical masses of  $h_1(1170)$ ,  $h'_1(1380)$  and the newly discovered  $h_1(1600)$  at  $1594 \pm 15^{+10}_{-60}$  MeV [8] are used as input. We further assume that the difference between the primitive  $s\bar{s}$  and  $u\bar{u} + d\bar{d}$  masses is the same for the ground states and excited states. Lastly, the primitive excited  $u\bar{u} + d\bar{d}$  mass, the most uncertain input, is taken as  $1650 \pm 50$  MeV. This is hence the assumed mass region for the yet undiscovered excited  $b_1$  resonance.

The output of our analysis is as follows. The experimentally unobserved physical excited  $s\bar{s}$  state ( $|h'_1\rangle_2$ ) is predicted at  $1810 \pm 40$  MeV. The difference between the primitive  $s\bar{s}$  and  $u\bar{u} + d\bar{d}$  masses, for both the ground and excited states, is  $180 \pm 10$  MeV, yielding a primitive  $s\bar{s}$  ground state ( $|s\bar{s}\rangle_1$ ) at  $1410 \pm 10$  MeV. This is consistent with  $1445 \pm 41$

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MeV derived from quark model relations<sup>3</sup>. The coupling, in the notation of refs. [2,3] is  $g_1 = 0.19 \pm 0.01$  GeV for the ground states and  $g_2 = 0.19 \pm 0.12$  GeV for the excited states. The accurate former value is larger than values found for scalar and tensor mesons [2,4].

The valence content of the physical mesons is

$$\begin{aligned} |h_1\rangle_1 &= (-0.22_{-0.01}^{+0.02})|g\rangle + (0.06_{-0.05}^{+0.03})|s\bar{s}\rangle_2 + (0.12_{-0.09}^{+0.05})|u\bar{u}\rangle_2 + (0.17_{-0.00}^{+0.01})|s\bar{s}\rangle_1 + (\mathbf{0.95}_{-0.01}^{+0.01})|u\bar{u}\rangle_1, \\ |h'_1\rangle_1 &= (-0.13_{-0.03}^{+0.02})|g\rangle + (0.06_{-0.05}^{+0.03})|s\bar{s}\rangle_2 + (0.13_{-0.11}^{+0.08})|u\bar{u}\rangle_2 + (\mathbf{0.96}_{-0.03}^{+0.02})|s\bar{s}\rangle_1 + (-0.22_{-0.03}^{+0.02})|u\bar{u}\rangle_1, \\ |h_1\rangle_2 &= (-0.19_{-0.08}^{+0.15})|g\rangle + (0.16_{-0.16}^{+0.09})|s\bar{s}\rangle_2 + (\mathbf{0.94}_{-0.08}^{+0.07})|u\bar{u}\rangle_2 + (-0.20_{-0.11}^{+0.16})|s\bar{s}\rangle_1 + (-0.14_{-0.06}^{+0.11})|u\bar{u}\rangle_1, \\ |h'_1\rangle_2 &= (-0.12_{-0.01}^{+0.07})|g\rangle + (\mathbf{0.97}_{-0.03}^{+0.04})|s\bar{s}\rangle_2 + (-0.21_{-0.13}^{+0.22})|u\bar{u}\rangle_2 + (-0.06_{-0.00}^{+0.03})|s\bar{s}\rangle_1 + (-0.05_{-0.00}^{+0.03})|u\bar{u}\rangle_1. \end{aligned}$$

where the states on the left and right are respectively the physical and primitive states. The first three physical states are the experimental states  $h_1(1170)$ ,  $h'_1(1380)$  and  $h_1(1600)$  [1].

Decays are now studied by using a finite width for the initial meson, and unless otherwise indicated, a narrow width approximation for the final mesons. Finite widths are implemented by smearing over relativistic Breit–Wigner shapes with Quigg – von Hippel energy dependent widths. Whenever a decay is OZI allowed from an ideally mixed initial state, we assume, for simplicity, that the initial state is 100% ideally mixed. OZI forbidden decays are implemented by using the (small) valence contents above to calculate connected decays [2].

The decays of conventional mesons are studied in the  $^3P_0$  model using the methods, conventions and parameters of refs. [2,9]. Making the usual identification that the primitive ground state mesons are P-wave quark model states, we obtain the decay widths in Table 1. We note that although the experimentally observed  $K^*K$  mode is dominant, and similar to the total width of the state<sup>4</sup> [1], the  $\rho\pi$  mode is detectable. It is not as large relative to  $K^*K$  as one might expect from the limited phase space of  $K^*K$ . Identification in  $\rho\pi$  is complicated by the huge  $360 \pm 40$  MeV width of the  $h_1(1170)$  mainly in  $\rho\pi$  [1]. This makes  $\rho\pi$  an unattractive search channel for  $h'_1(1380)$ , since no viable production processes are known which strongly produce the dominant  $s\bar{s}$  component in  $h'_1(1380)$  as opposed to the dominant  $u\bar{u} + d\bar{d}$  component in  $h_1(1170)$ . Although  $\omega\eta$  is small,  $h'_1(1380)$  has recently been observed in this mode [10]. Additional decay modes that have not been calculated but are expected to be small are decays to  $h_1(\pi\pi)_S$  and direct three-body decays like  $\pi^0\pi^+\pi^-$ .

We proceed to analyse  $h_1(1600)$ . One has to allow for the possibility that the excited  $u\bar{u}$ ,  $d\bar{d}$  and  $s\bar{s}$  states are hybrid mesons. The calculations for this possibility are performed in the Isgur–Paton flux–tube model with the standard parameters of ref. [11].

<sup>3</sup>Combining  $K(^1P_1) + K(^3P_1) = K(1270) + K(1400)$ ,  $b_1 + (s\bar{s})_1 = 2K(^1P_1)$  and  $K(^1P_1) - b_1 = K(^3P_1) - a_1$ . Here all items are the corresponding masses. The  $^1P_1$  and  $^3P_1$  kaon masses before mixing are  $K(^1P_1)$  and  $K(^3P_1)$  respectively, and the primitive  $s\bar{s}$  ground state mass is  $(s\bar{s})_1$ .

<sup>4</sup>We find that mock meson phase space [13] gives a  $K^*K$  partial width of  $191 \pm 18$  MeV, inconsistent with the experimental total width of the state [1]. For near threshold decays of this type mock meson phase space always gives a substantially larger width than relativistic phase space. Mock meson phase space results are hence not quoted for near threshold decays in the tables. We note that the  $K^*K$  partial width calculation in ref. [13] misses a flavour factor of two, and is hence unreliable.

Table 1

Partial decay widths of  $h_1'(1380)$  in MeV in relativistic [9] and mock meson [13] phase space. The latter is in brackets. For conventional meson decays in relativistic phase space we allow the wave function parameter  $\beta$ , which is taken to be the same for the incoming and outgoing states in a decay, to vary between the reasonable values 0.35 and 0.45 GeV [9], giving rise to the error estimate. The dagger indicates that phase space is unreliable in the narrow resonance approximation for the final state, so that the width is calculated by smearing over a Breit–Wigner for all broad resonances involved, both in the initial and final states. Since the  $|u\bar{u}\rangle_2$  component of the physical  $h_1'(1380)$  has such a large uncertainty, we only employ the  $|u\bar{u}\rangle_1$  component for OZI forbidden decays. However, omission of the  $|u\bar{u}\rangle_2$  component could significantly affect widths and especially  $D/S$ -wave width ratios.

Mode	Wave	Width
$K^*K$ †	S	$137 \pm 12$
	D	$1 \pm 1$
	D/S	$0.010^{+0.008}_{-0.004}$
$\rho\pi$	S	$12 \pm 3$ (13)
	D	$4 \pm 3$ (4)
	D/S	$0.4^{+0.4}_{-0.2}$ (0.4)
$\omega\eta$	S	$2 \pm 1$ (2)
	D	0 (0)
	D/S	$0.01^{+0.01}_{-0.00}$ (0.01)
$b_1\pi$ †	P	0
Total		156

The results are displayed in Table 2. The  $h_1(1600)$  is predicted to decay from most to least prevalent to  $\rho\pi / \rho(1450)\pi$ ,  $K^*K$  and  $\omega\eta$  in all interpretations of the state. A minor feature that distinguishes interpretations is the relative size of the  $\rho\pi$  and the  $\rho(1450)\pi$  modes. The main distinguishing feature is the ratio of  $D$ -wave to  $S$ -wave widths, which is consistently larger for the meson than the hybrid interpretation. For the meson interpretation the  $S$ -wave width is suppressed due to a node in the amplitude, making it sensitive to the wave function parameter  $\beta$  employed. Table 2 shows that the  $D/S$ -wave width ratio in  $\omega\eta$  is inconsistent with the experimental result  $0.3^{+0.1}_{-0.1-3}$  [12] if  $h_1(1600)$  is a conventional meson. In order to confirm this result, we perform three further checks. Firstly, we evaluate the ratio by taking the wave function parameter  $\beta$  to be different for different mesons participating in the decay. Varying  $\beta$  in the reasonable range 0.35 – 0.45 GeV [9] confirms the result. Secondly, using the full valence content of  $h_1(1600)$  above, and allowing decay via the ground state P-wave meson component, confirms the result. Thirdly, experimental data has few D-wave events above 1.8 GeV [8]. Restricting the Breit–Wigner smearing to invariant masses less than 1.8 GeV gives the nearest ratio to experiment in all these simulations,  $0.9^{+1.2}_{-0.5}$ . This ratio is still outside the range allowed

Table 2

Partial decay widths of pure  $u\bar{u} + d\bar{d}$   $h_1(1594)$  (with the experimental total Breit–Wigner width 384 MeV) in MeV for its interpretations as conventional and hybrid mesons. Hybrid meson decays are calculated in the IKP and PSS models [11]. Other conventions are as in Table 1.  $h_1(1594) \rightarrow h_1(\pi\pi)_S$  is not estimated.

Mode	Wave	Meson	IKP Hybrid	PSS Hybrid
$\rho\pi$	S	$14 \pm 2$ (13)	111 (96)	86 (74)
	D	$126 \pm 40$ (97)	1 (1)	1 (1)
	D/S	$9^{+1}_{-5}$ (7)	0.005 (0.004)	0.009 (0.008)
$\rho(1450)\pi^\dagger$	S	$31 \pm 1$	142	111
	D	$6 \pm 3$	0	0
	D/S	$0.2 \pm 0.1$	0.0002	0.0004
$K^*K$	S	$15 \pm 3$ (17)	27 (31)	37 (42)
	D	$17 \pm 7$ (17)	0 (0)	0 (0)
	D/S	$1.2^{+1.1}_{-0.6}$ (1.0)	0.0004 (0.0003)	0.0005 (0.0005)
$\omega\eta$	S	$6 \pm 2$ (6)	19 (18)	24 (23)
	D	$11 \pm 5$ (10)	0 (0)	0 (0)
	D/S	$1.8^{+1.8}_{-0.8}$ (1.6)	0.002 (0.001)	0.003 (0.002)
$b_1\pi$	P	0	136 (227)	0 (0)
Total		225	436	259

by experiment, although it is not far outside the range. Experimentally, it has not been established that the D–wave exists [12], so that the very small ratio predicted for a hybrid meson in Table 2 could be consistent with experiment. Thus current experiment makes the conventional meson interpretation of the  $h_1(1600)$  unlikely, but allows the hybrid interpretation. This assumes that the state observed in experiment cannot be resolved into two separate states. Since the  $^3P_0$  model has only been tested for a few  $D/S$ –wave width ratios [9], one needs further information. The total width  $384 \pm 60^{+70}_{-100}$  MeV of  $h_1(1600)$  is slightly more consistent with the hybrid interpretation. Future searches for  $h_1(1600)$  should focus on obtaining the  $D/S$ –wave width ratio in the sizable  $\rho\pi$  channel. The  $b_1\pi$  mode distinguishes the two models of hybrid decay in Table 2.

We note that since the  $\rho$  Regge trajectory dominates the  $\rho(1450)$  and  $b_1$  trajectories, and  $h_1(1600)$  has a healthy  $\rho\pi$  coupling for all interpretations, one expects the  $h_1(1600)$  to be produced via natural parity exchange in the  $\pi^-p$  collisions it has been observed in. This is confirmed in the experimental analysis [8], providing an independent check on our calculations. The non–observation of  $h_1(1600)$  in unnatural parity exchange [8] may put bounds on its  $b_1\pi$  coupling, discriminating between different hybrid decay models.

In Table 3 the widths for the isopartner state  $b_1(1650)$  are calculated. The channels that distinguish between conventional and hybrid meson interpretations of the state,  $\omega(1420)\pi$  and  $\rho\rho$ , are difficult to access experimentally. However,  $D/S$ –wave width ratios remain an excellent distinguishing feature. Possible search channels are  $\omega\pi$  and  $\rho\eta$ .

Table 3

Partial decay widths of  $b_1(1650)$  in MeV. Conventions are as in Table 2, including using the same total width for  $b_1(1650)$  as for  $h_1(1594)$ .  $b_1(1650) \rightarrow b_1(\pi\pi)_S$  is not estimated.

Mode	Wave	Meson	IKP Hybrid	PSS Hybrid
$\omega\pi$	S	$4^{+2}_{-0}$ (4)	37 (30)	28 (22)
	D	$48 \pm 13$ (35)	0 (0)	0 (0)
	D/S	$11^{+0}_{-3}$ (9)	0.006 (0.005)	0.01 (0.01)
$\omega(1420)\pi^\dagger$	S	$11 \pm 1$	70	54
	D	$7 \pm 3$	0	0
	D/S	$0.6^{+0.6}_{-0.2}$	0.0009	0.001
$K^*K$	S	$13 \pm 3$ (14)	30 (32)	40 (42)
	D	$23 \pm 9$ (22)	0 (0)	0 (0)
	D/S	$1.8^{+1.7}_{-0.9}$ (1.5)	0.0005 (0.0004)	0.0007(0.0007)
$\rho\rho^\dagger$	S	$34 \pm 6$	0	0
	D	$34 \pm 15$	0	0
	D/S	$1.0^{+0.8}_{-0.4}$		
$\rho\eta$	S	$5 \pm 1$ (5)	20 (18)	25 (22)
	D	$15 \pm 6$ (12)	0 (0)	0 (0)
	D/S	$3.1^{+2.6}_{-1.6}$ (2.6)	0.002 (0.002)	0.003 (0.003)
$a_0\pi^\dagger$	P	$8 \pm 1$	56	3
$a_1\pi$	P	$11 \pm 2$ (16)	19 (30)	3 (5)
$a_2\pi$	P	$82 \pm 16$ (132)	37 (60)	7 (12)
	F	$3^{+4}_{-2}$ (4)	0 (0)	0 (0)
	F/P	$0.03^{+0.04}_{-0.01}$ (0.03)	0.005 (0.005)	0.0003 (0.0003)
$h_1\pi$	P	0	72 (108)	0 (0)
Total		296	341	160

The widths for the undiscovered excited  $s\bar{s}$  state  $h'_1(1810)$  are indicated in Table 4. It is interesting to note that the flux-tube model selection rule, which states that decays to  $S + S$  states ( $K^*K$ ,  $\phi\eta$ ) are suppressed relative to  $P + S$  states ( $K_1(1270)K$ ) [11], is apparently violated. This is due to phase space. Whether the  $h'_1(1810)$  is a conventional or hybrid meson, it is surprisingly narrow. Excellent search channels are  $K^*K$  and  $\phi\eta$ . The latter is especially interesting since it cannot come from a  $u\bar{u} + d\bar{d}$  state via OZI allowed decay. Small OZI forbidden modes like  $\rho\pi$  could also effect detection. A natural place to search for  $s\bar{s}$  states is at Jefferson Lab, where the photon has a sizable coupling to  $s\bar{s}$ . Production is likely to be via diffractive exchange, as meson exchange involves OZI forbidden or evading processes.

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Table 4

Partial decay widths of pure  $s\bar{s}$   $h'_1(1810)$  in MeV. Conventions are as in Table 2, except that  $h'_1$  has a total width of 100 MeV.  $h'_1(1810) \rightarrow h'_1(1380)(\pi\pi)_S$  is not estimated.

Mode	Wave	Meson	IKP Hybrid	PSS Hybrid
$K^*K$	S	$11 \pm 9$ (10)	47 (43)	47 (43)
	D	$70 \pm 30$ (61)	0 (0)	0 (0)
	D/S	$6^{+22}_{-4}$ (6)	0.004 (0.004)	0.009 (0.008)
$\phi\eta$	S	$17 \pm 5$ (18)	22 (24)	56 (60)
	D	$14 \pm 7$ (14)	0 (0)	0 (0)
	D/S	$0.8^{+1.3}_{-0.4}$ (0.8)	0.0004 (0.0004)	0.0006 (0.0006)
$K_1(1270)K \dagger$	P	$1 \pm 0$	13	0
Total		113	82	103

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